LSSO: Precision Lunar Laser Ranging

Stephen Merkowitz, David Arnold, Philip Dabney, Jeffrey Livas, Jan McGarry, Gregory Neumann, Thomas Zagwodzki

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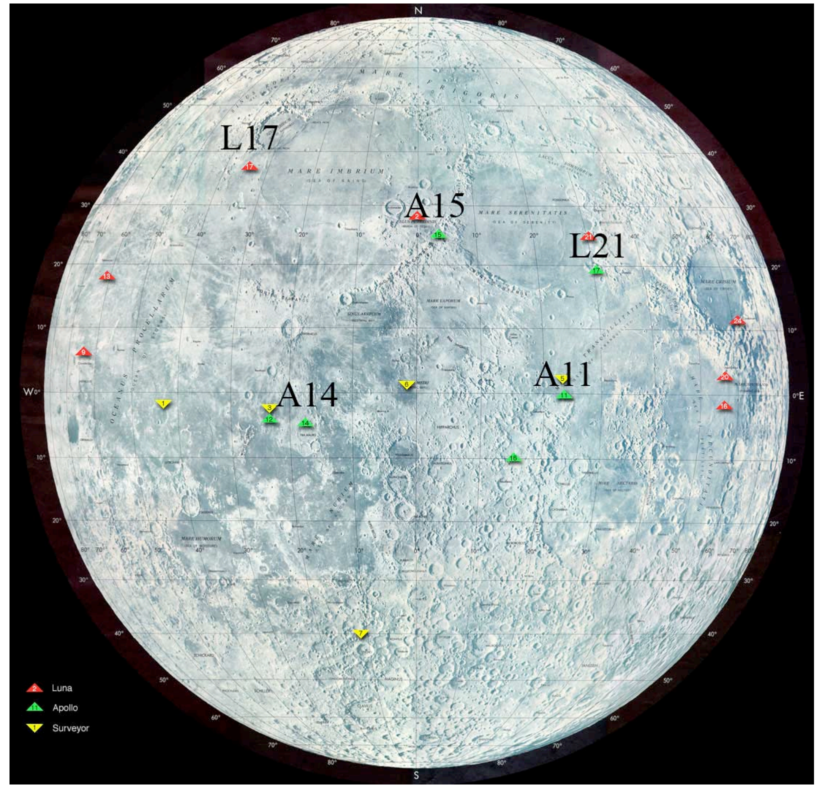
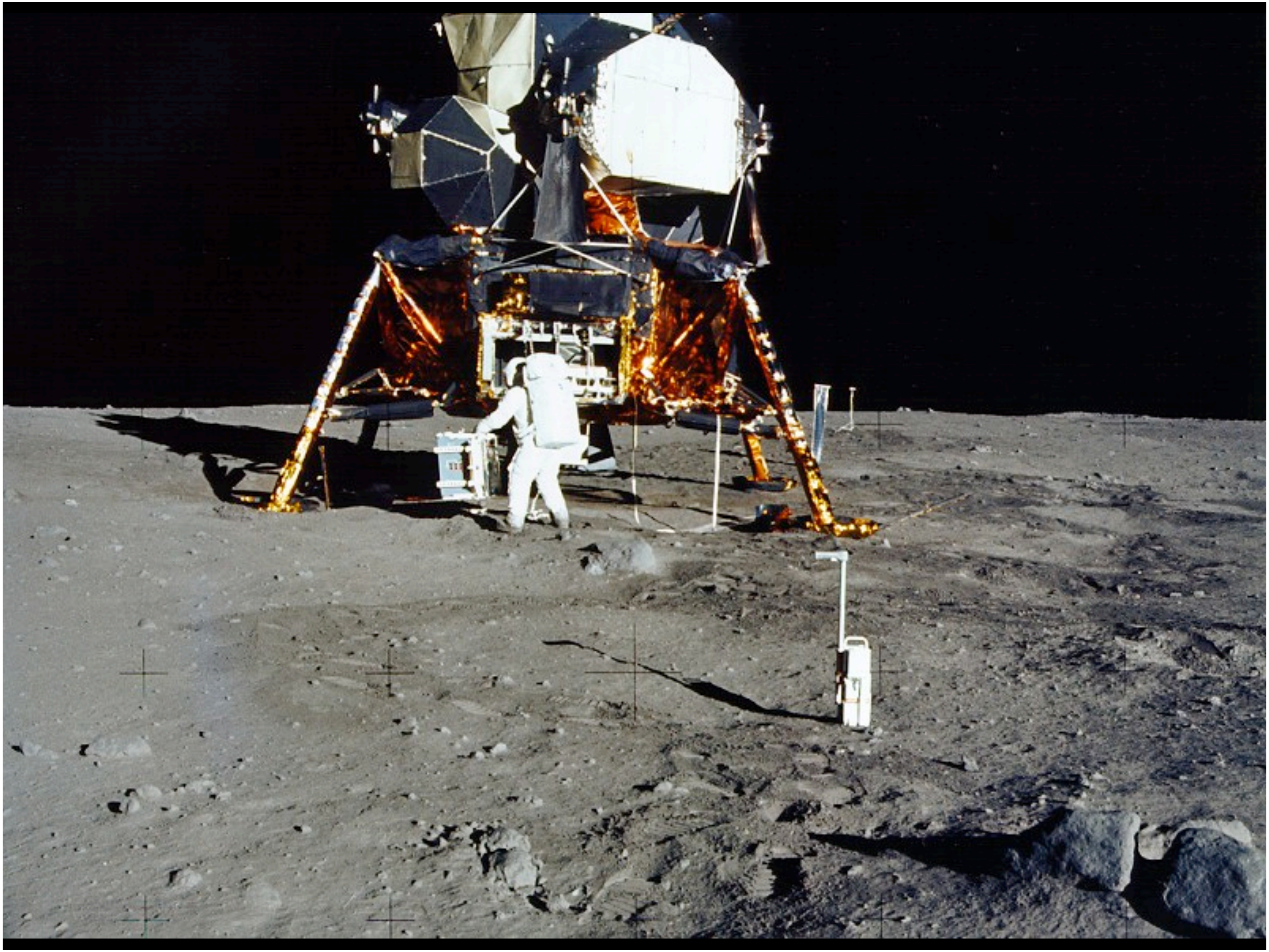
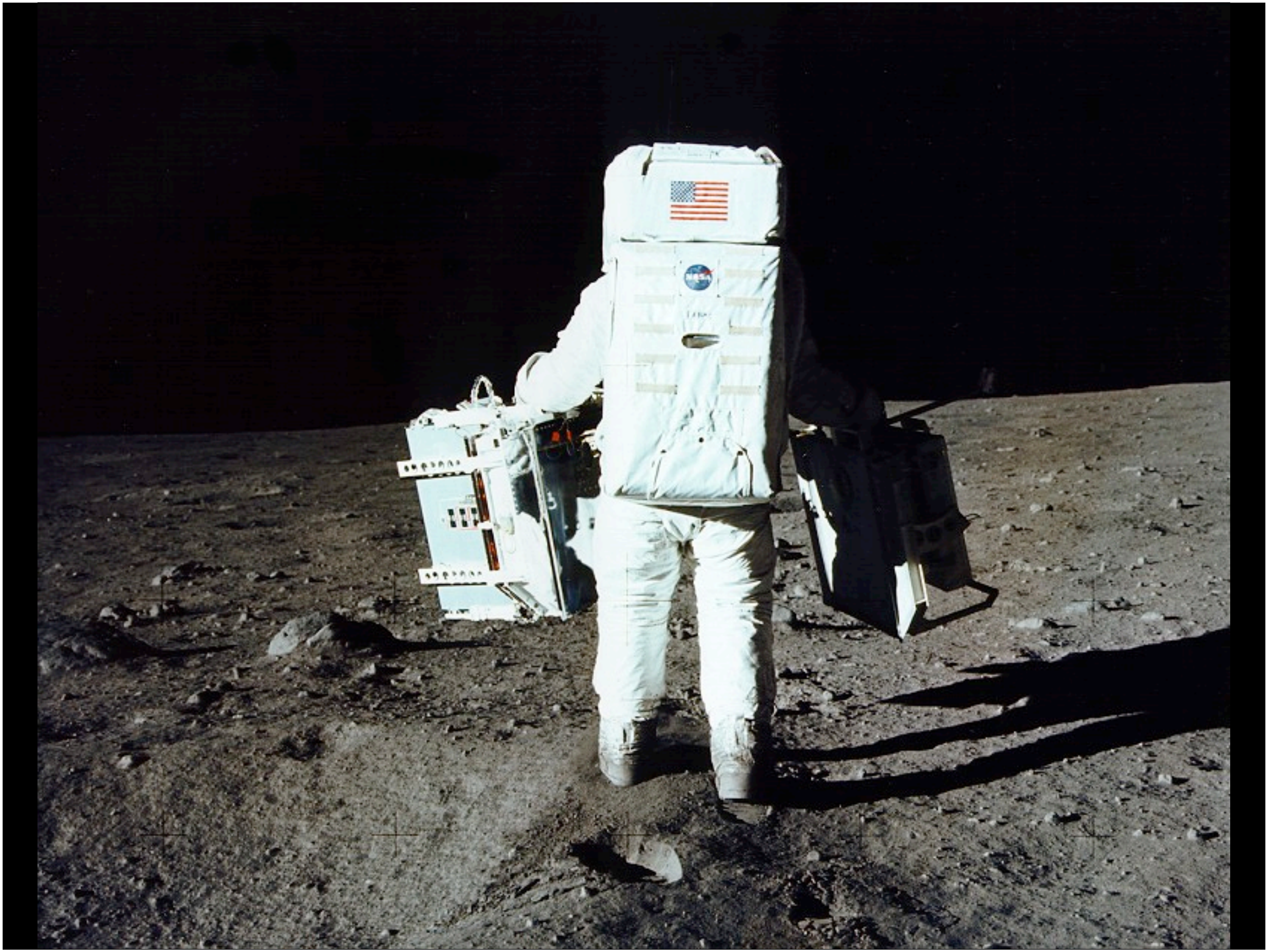
Lunar Laser Ranging Background

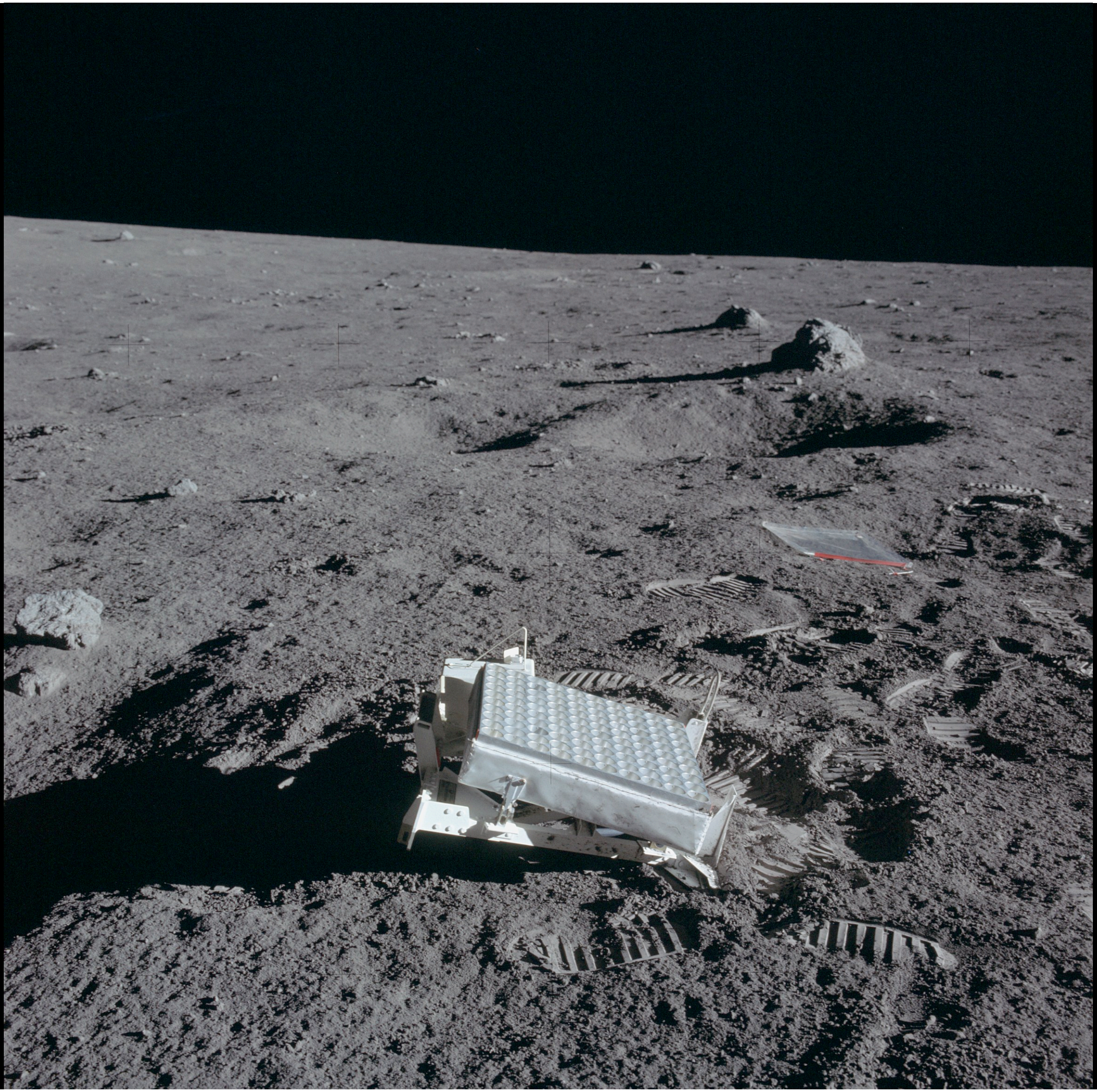
- First suggested by R. H. Dicke in early 1950s.
- MIT and soviet Union bounced laser light off lunar surface in 1960s.
- Retroreflectors proposed for Surveyor missions but not flown.
- Retroreflectors flown on 3 Apollo missions.



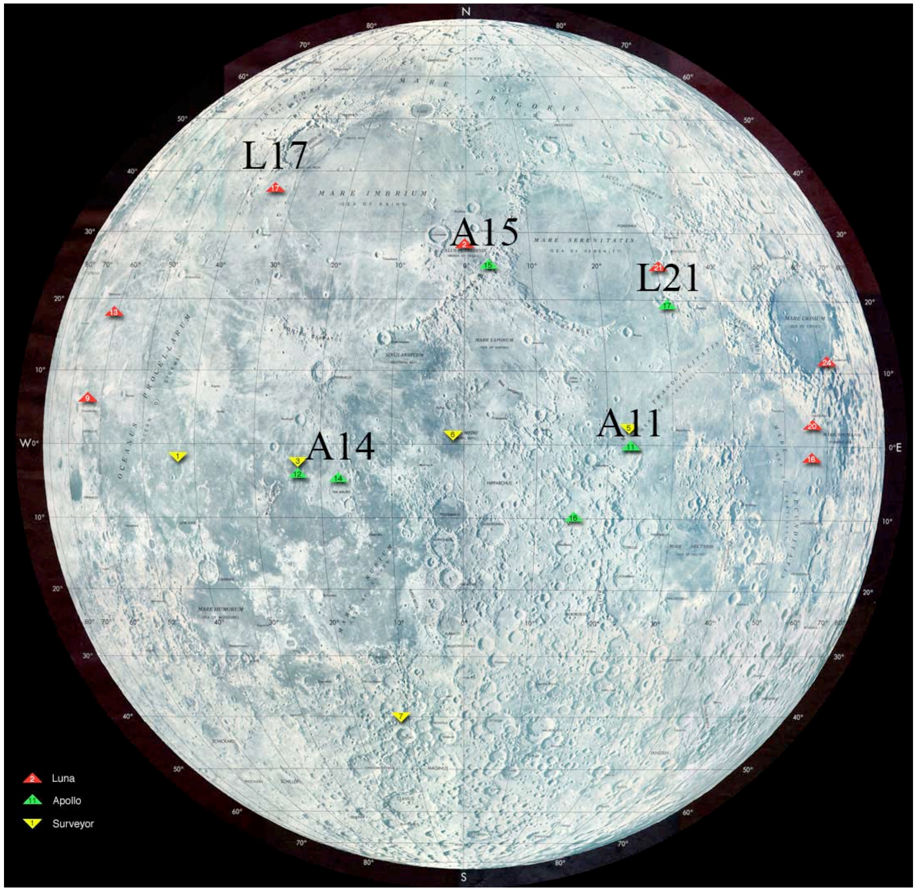
  - Apollo arrays used fused silica “circular opening” cubes, 3.8 cm diameter each
  - Apollo 11 and 14 arrays used 100 cubes
  - Apollo 15 used 300 cubes

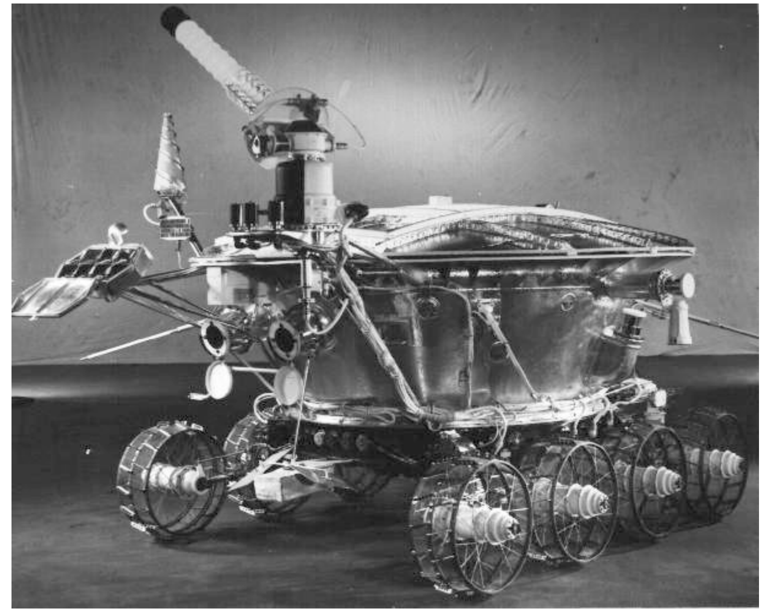




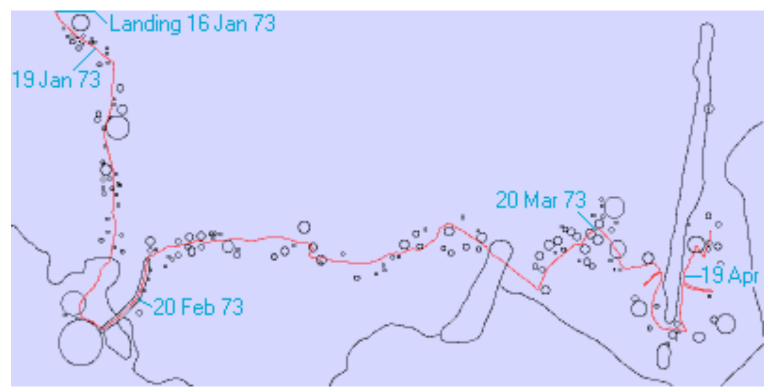


Soviet Luna Missions





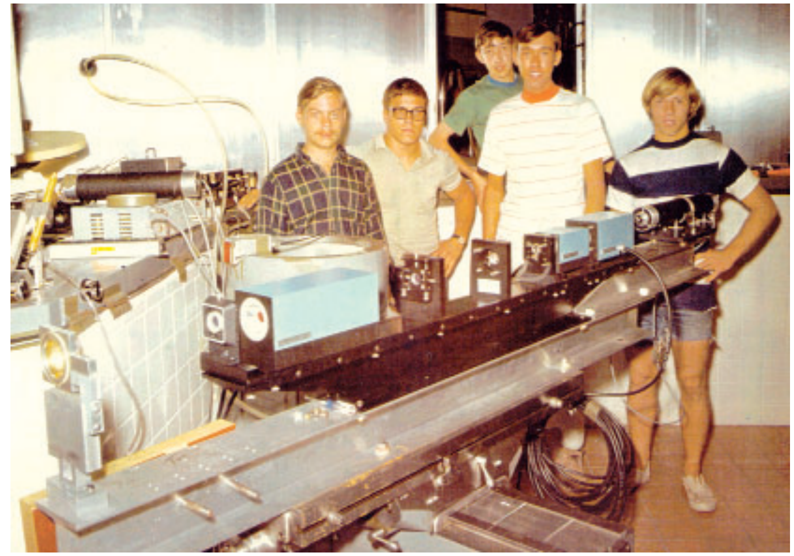
Lunokhod



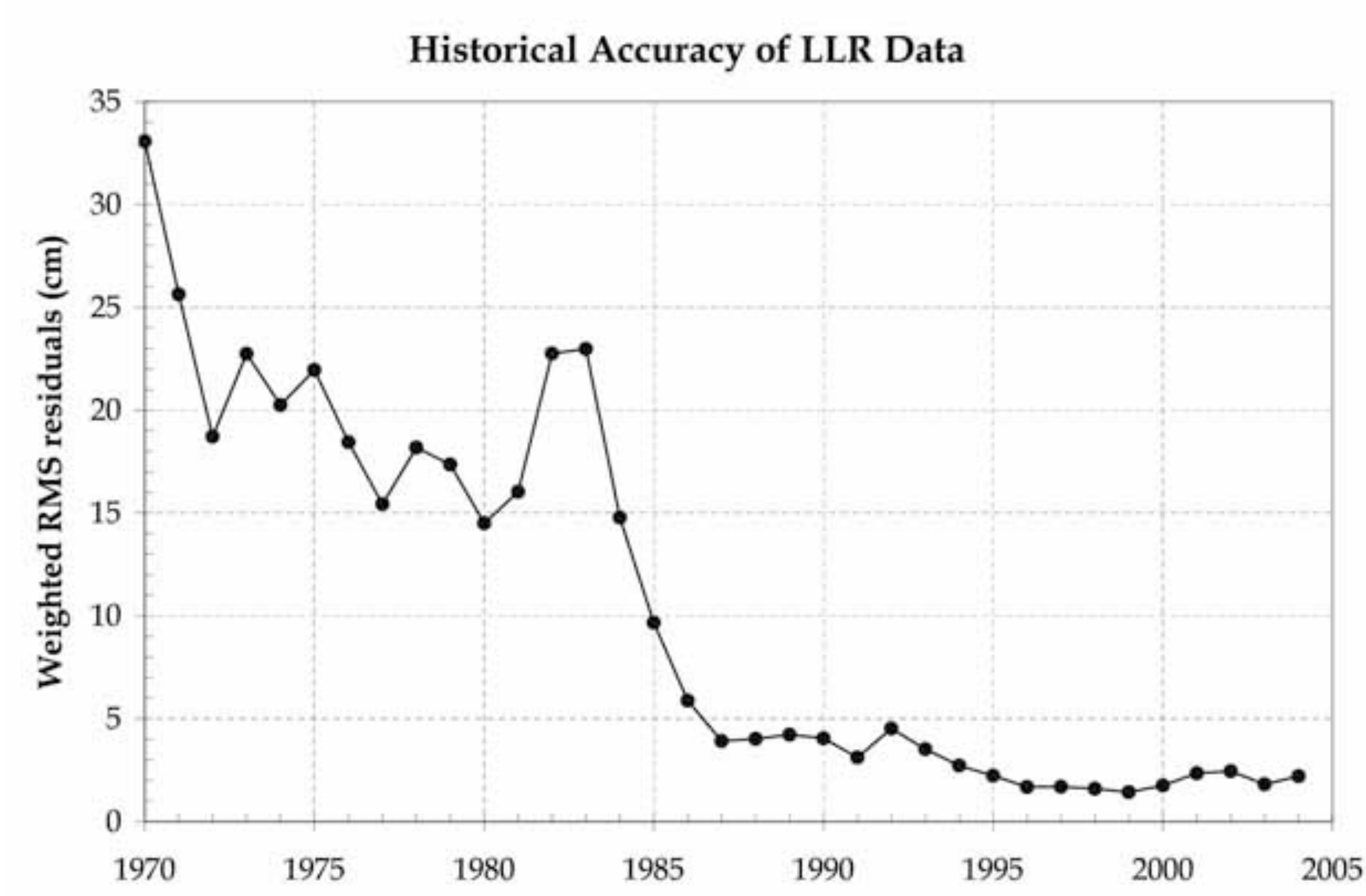
- Lunokhod arrays consist of 14 triangular shaped cubes, each side 11cm
- Only Lunokhod 2 is still visible

39 Years of LLR and Still Going

- Lick Observatory in California got first light in 1969.
- McDonald Observatory in Texas 1969 to present!
- Other early ranges:
  - Crimean astrophysical observatory in the Soviet Union,
  - Orroral Observatory in Australia,
  - Air Force Cambridge Research Laboratories Lunar Ranging Observatory in Arizona,
  - The Pic du Midi Observatory in France (Calame et al., 1970),
  - Tokyo Astronomical Observatory
- Orroral Observatory in Australia 1978 to 1980.
- Observatoire de la Côte d'Azur (OCA) in France 1984 to present.
- Haleakala Observatory on Maui in Hawaii 1984 to 1990.
- Apache Point Observatory in New Mexico is now in operation with mm level precision.

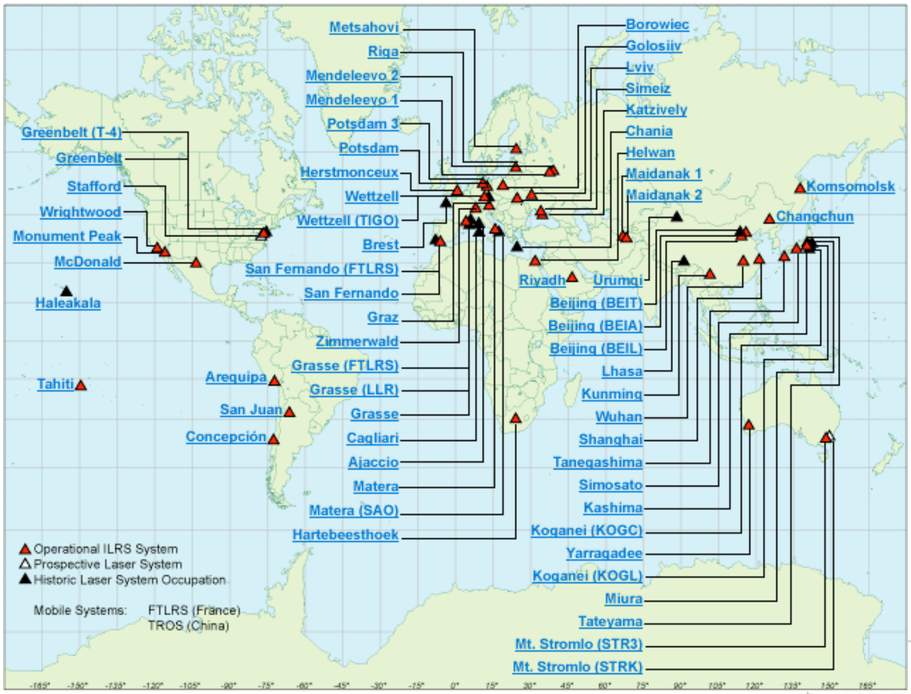


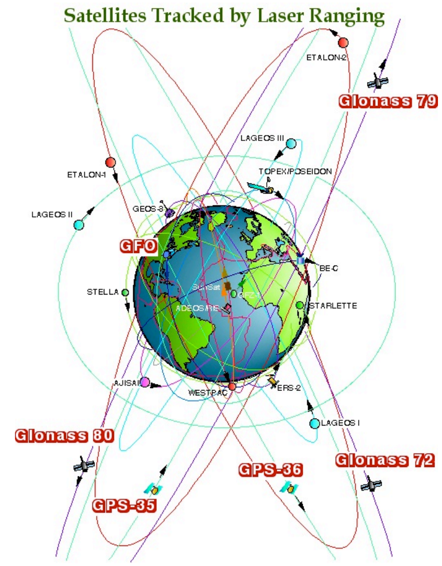
History of LLR



J. G. Williams *et al.*, gr-qc/0507083

Satellite Laser Ranging (SLR)

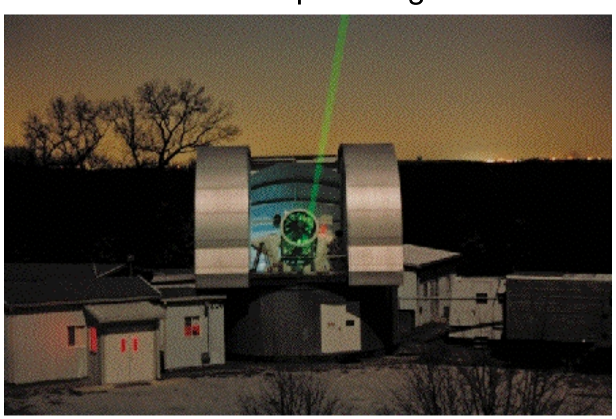


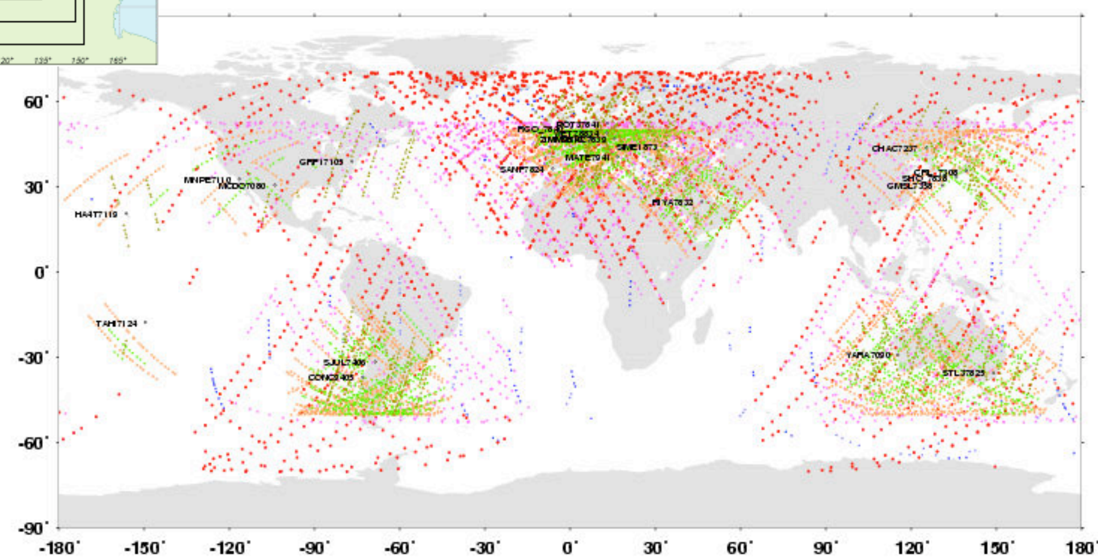


LAGEOS

~35 stations in operation tracking over 100 satellites

Satellite Laser Ranging began in 1964 at NASA Goddard Space Flight Center.





http://ilrs.gsfc.nasa.gov/

Science of LLR

- Lunar ephemerides are a product of the LLR analysis used by current and future spacecraft missions.
  - Lunar ranging has greatly improved knowledge of the Moon's orbit, enough to permit accurate analyses of solar eclipses as far back as 1400 B.C.
- Gravitational physics:
  - Tests of the Equivalence principle
  - Limits on the time variation of the gravitational constant G,
  - Relativistic precession of lunar orbit (geodetic precession).
  - Accurate determination of the PPN parameter β,γ,
- Lunar Science:
  - Lunar tides
  - Interior structure (fluid core)

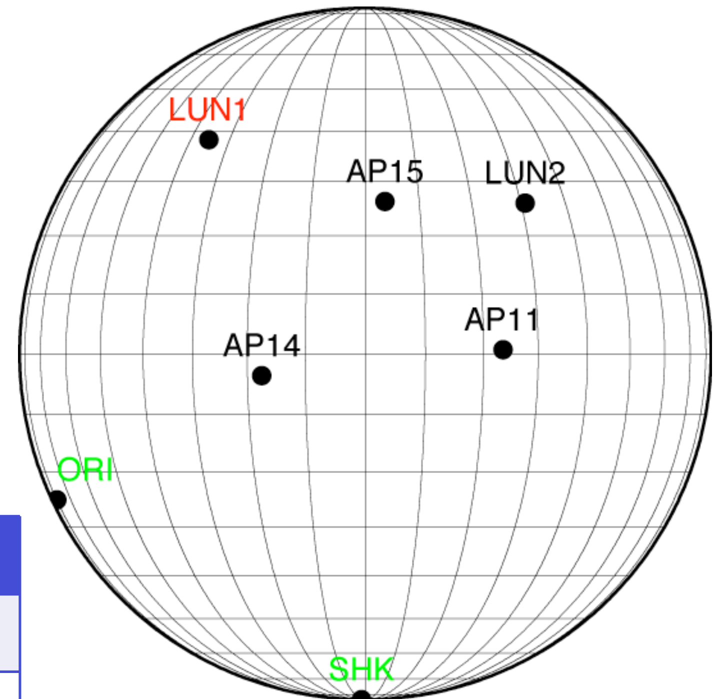
	Current	w/ 1 mm
WEP $\Delta a/a$	$(-1.0\pm1.4)\times10^{-13}$	10^{-14}
SEP η	$(4.4\pm4.5)\times10^{-4}$	3×10^{-5}
$\dot{G}/G$	$(4\pm9)\times10^{-13}$/year	10^{-13}/year
Geodetic Precession K_{gp}	$(-1.9\pm6.4)\times10^{-3}$	3×10^{-4}

Next Generation LLR Instruments

- Increased precision and coverage to expand scientific and navigational results:
  - New lunar sites.
  - Lower systematic and statistical errors.
  - Take advantage of existing satellite laser ranging infrastructure.
- Pathfinder for Mars and other interplanetary ranging instruments.
- Provide additional services like laser communications.

New Ranging Sites

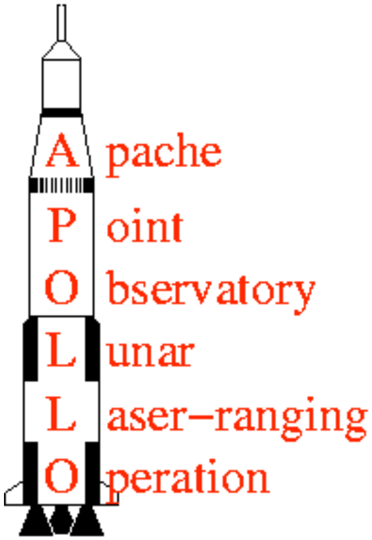
- Available retroreflectors all lie within 26 degrees latitude of the equator, and the most useful ones within 24 degrees longitude of the sub-earth meridian.
- Operating LLR stations are at similar northern latitudes.
- The addition of one or more reflectors would improve the geometrical precision of a normal point by a factor of 1.5 to nearly 4 at the same level of ranging precision.



	X	Y	Z	RotX	Rot Y	Rot Z
MLRS and OCA	0.265	6.271	23.294	15.958	0.179	0.225
25% of observations to ORI	0.263	3.077	23.305	7.611	0.174	0.140
25% of observations to SHK	0.259	2.840	23.271	4.692	0.114	0.198
both ORI and SHK	0.259	2.969	23.291	4.850	0.116	0.086
both ORI and SHK with 25% additional observations from Mt. Stromlo	0.030	2.501	2.902	4.244	0.050	0.078

S. M. Merkowitz *et al.*, Int. J. Mod. Phys. D **16**, 2151 (2007).

Apache Point Observatory



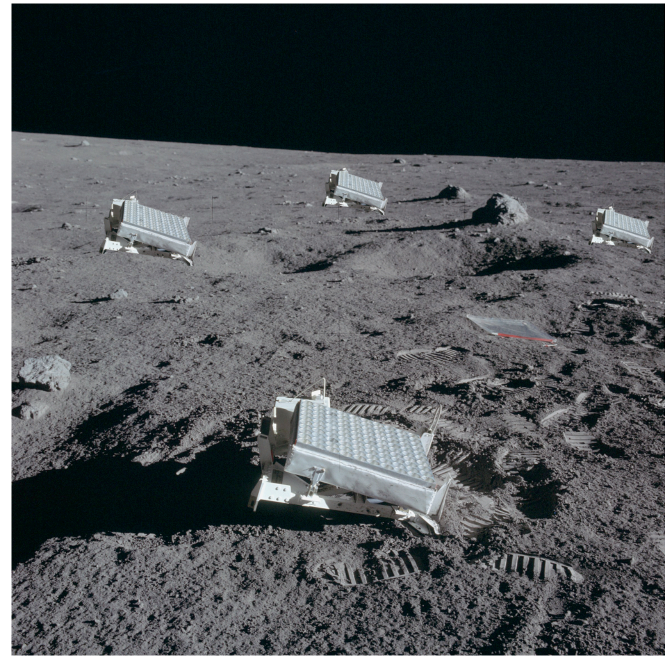
- Apache Point Observatory in New Mexico is operating with mm precision.
- 3.5 meter telescope.
- 2.3 Watt NdYAG laser

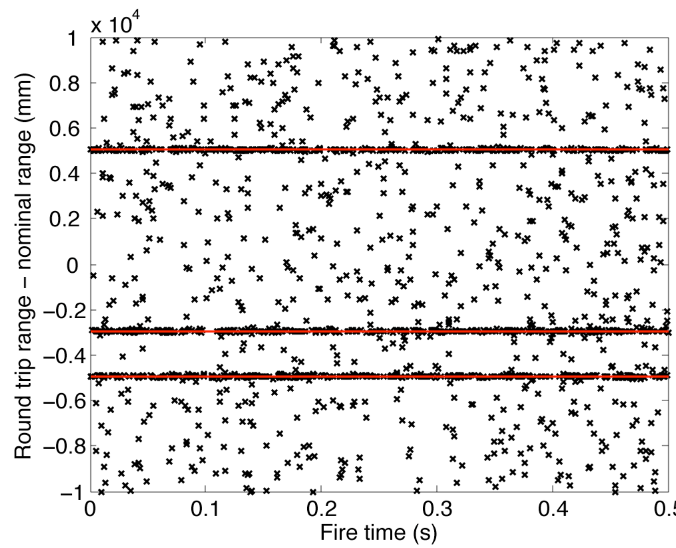
Error Source	Range error (mm)
Retro Array Orient.	15–45
APD Illumination	9
APD Intrinsic	< 7.5
Laser Pulse Width	7
Timing Electronics	3
GPS-slaved Clock	1
Total Random Error	**20–47**

T. W. Murphy *et al.*, Publ. Astron. Soc. Pac. **120**, 20 (2008).

Distributed Retroreflectors

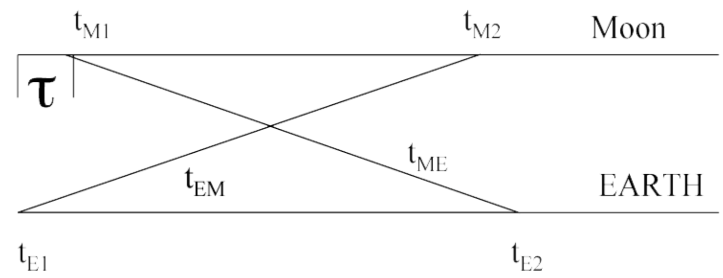
- Smaller arrays minimize orientation errors.
- Smaller arrays are less susceptible to thermal distortions.
- Smaller arrays are easier to deploy by the astronauts.
- Multiple arrays increase the cross-section.
- Light weight hollow cubes may be used to minimize mass.
- Beryllium hollow cubes potentially have small thermal distortions and may be made larger without sacrificing optical performance.



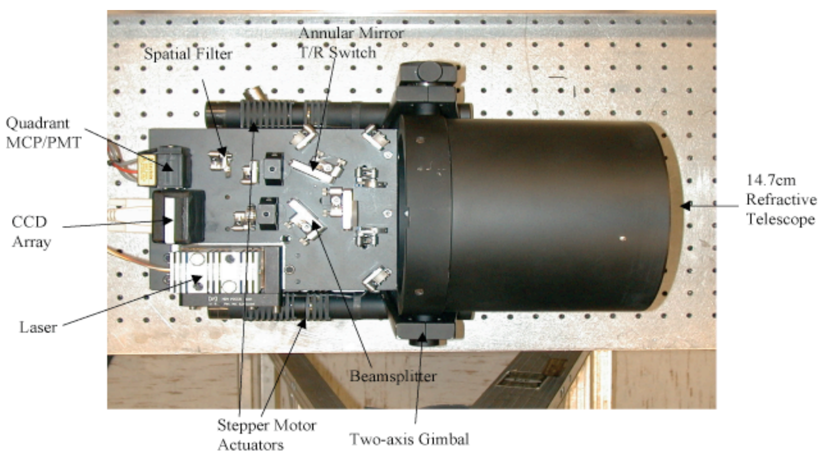


Asynchronous Transponder

- Transponders have only r^2 signal loss compared to r^4 for retroreflectors.
- Transponder would not have large orientation errors.
- Asynchronous Transponder could be used with existing SLR systems with little modification.



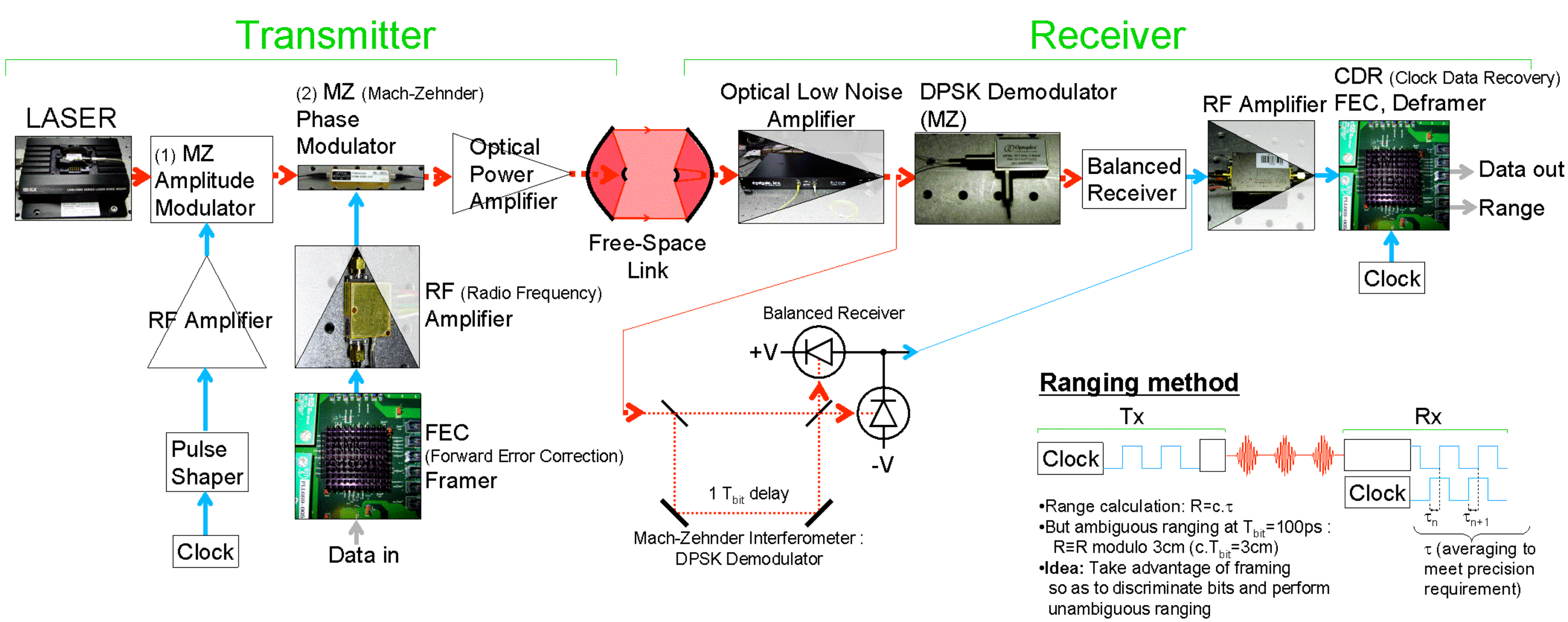
Parameter	1 cm Aperture	5 cm Auplink perture	40 cm Aperture
Wavelength (nm)	532	532	1064
Pulse energy	15 @ 2 kHz (uJ)	15 @ 2 kHz (uJ)	1 @ 10 kHz (uJ) (50% de-rating)
Divergence (μrad)	40	40	0.6
Atmospheric trans. (%)	49	49	49
Detector Detection Efficiency (%)	45	45	23
Optical T (%)	0.6	0.6	0.4
ND filter – Optical Density	0	1.5	0
Optical band-pass (FWHM) (Å)	1.7	1.7	0.28 (Etalon)
FOV (mrad) (divided by 4 quadrants)	0.6	0.6	40
Earth Albedo with Snow on ground	0.9	0.9	0.9
Noise rate per quadrant	220 kHz	175 kHz	80 kHz
Average Photo-electrons per fire (Detect Probability-DP) per quadrant	0.5 (0.4)	0.4 (0.35)	0.05 (0.17)
Ranging Event Rate	3.2 kHz	2.8 kHz	6.6 kHz



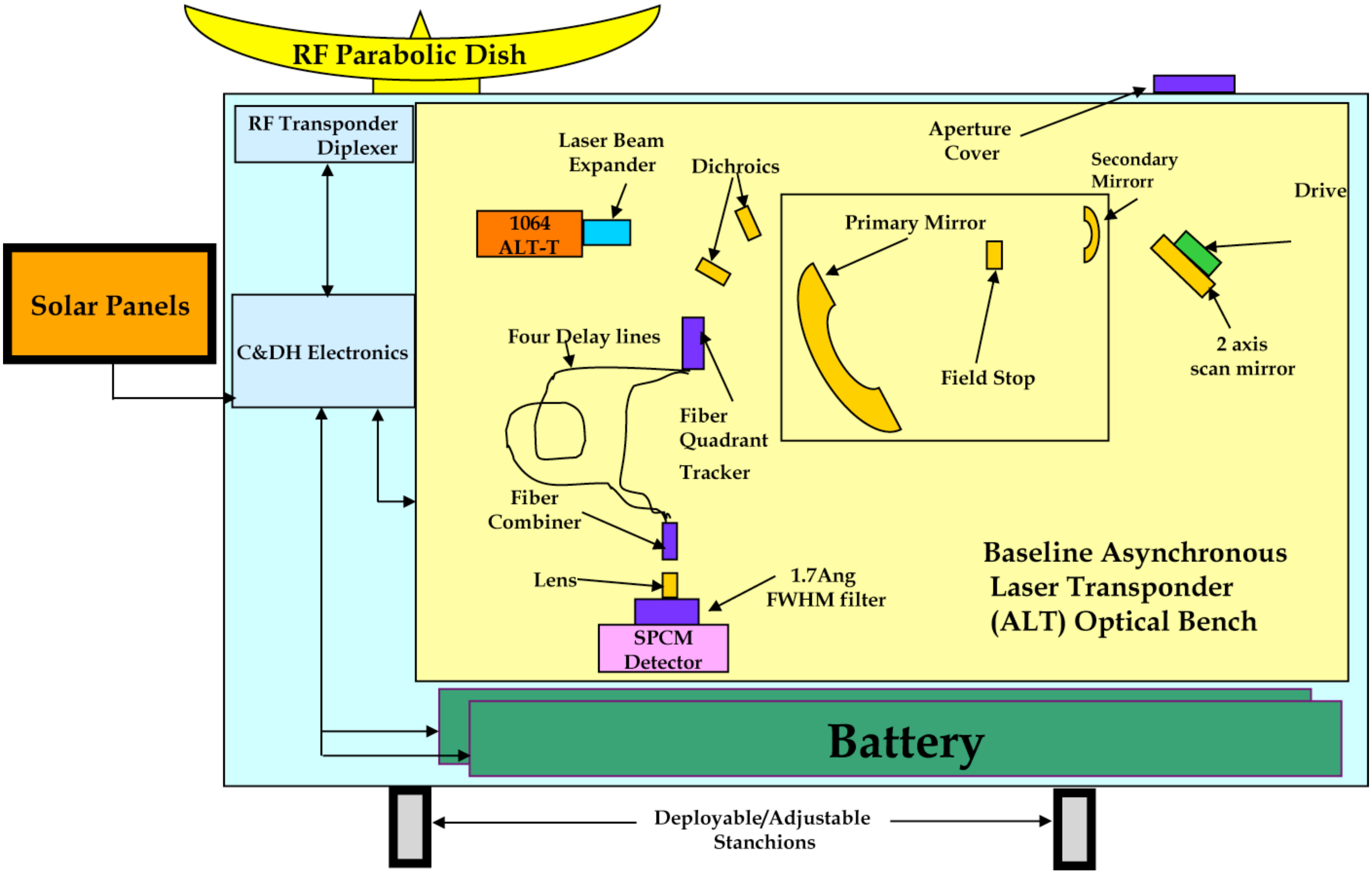
Optical Communications

- With an optical link it is natural to use it for communications in addition to ranging.
- Potentially higher capacity over large distances than RF communications.
- Several methods currently under development at GSFC.

Parameter	Downlink	Uplink
Wavelength (µm)	1.55	0.775
Data Rate (Mbps)	900	550
Tx aperture (cm)	5.00	40.00
Rx aperture (cm)	202.50	5.00
Code Rate	0.80	0.80
receiver sensitivity (photons/bit)	100	100
BER	1.50E-03	1.50E-03
Output power (W)	1	8
Transmitter losses (dB)	-3.8	-3.8
Net prop loss (dB)	-80.78	-88.85
Receiver losses (dB)	2	2
Net Rx power (dBm)	-52.58	-51.62
Net Margin (dB)	**0.86**	**0.95**



Standalone Package



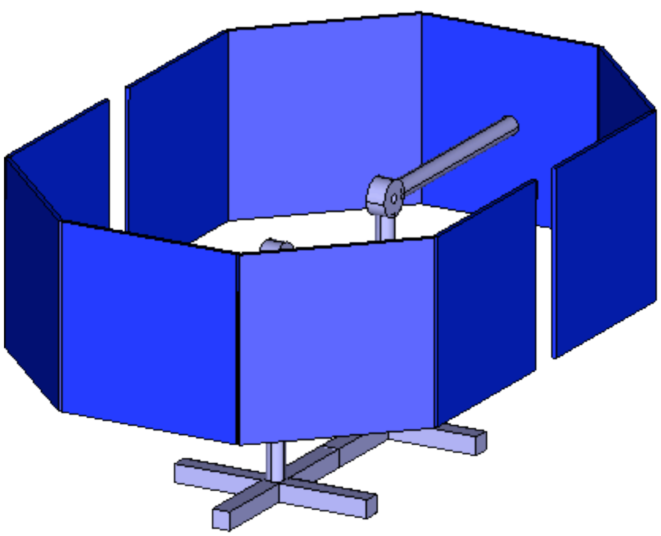
Polar Concept

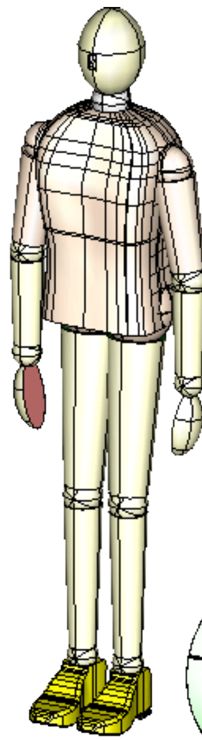
Power

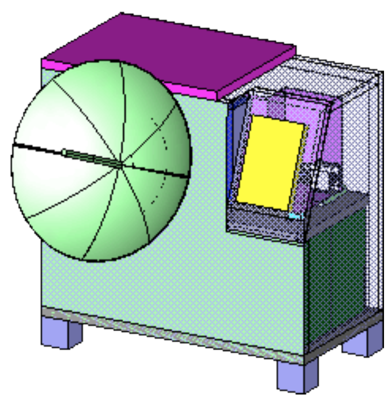
	Rangin g	Lasercom m	RF Transmi	Standb y
Power (W)	42.0	58.0	60.7	24

Mass

Item	Mass (Kg)
Laser Transponder Instrument	11.2
Transmitter Assembly	0.7
Receiver Assembly	4.5
Two-Axis Scan Mirror Assembly	1.1
Optical Assembly	3.3
C&DH Electronics	6.8
Batteries	77.7
RF Subsystem	9.6
Instrument Structure	14.3
Thermal Subsystem	21.0
Solar Array	10.5
TOTAL	**151.1**





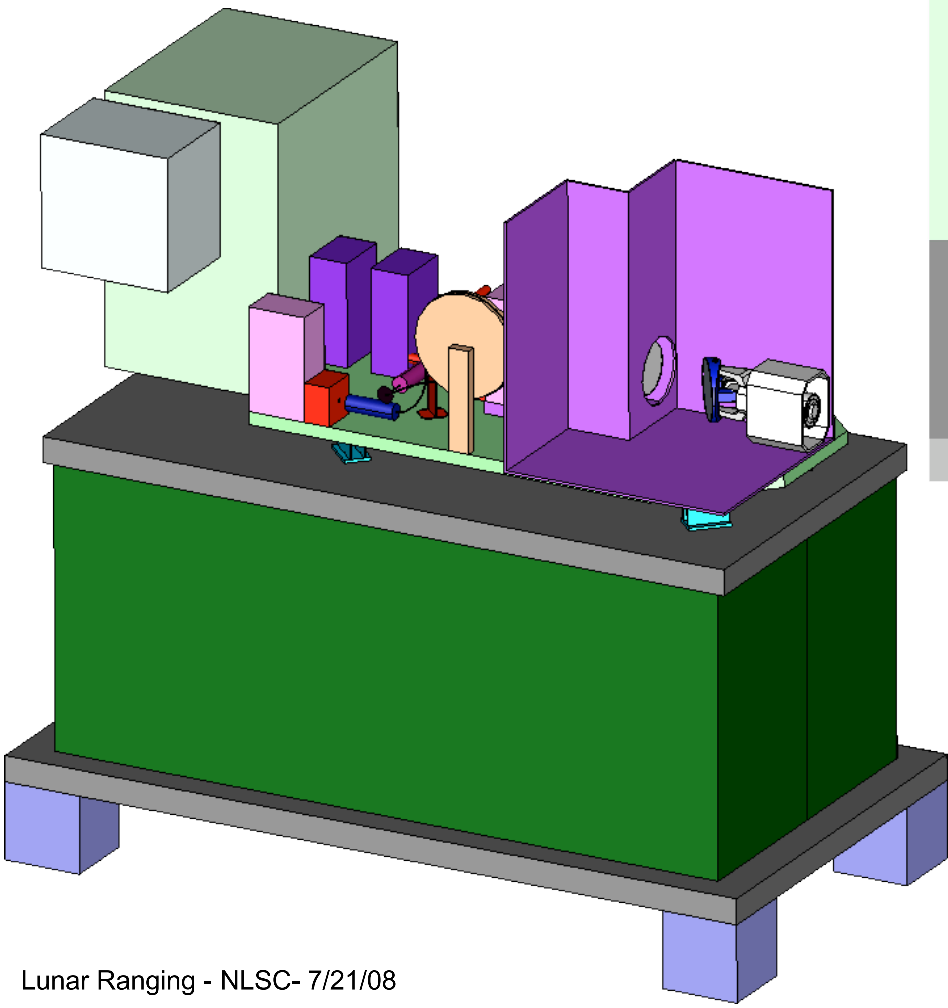


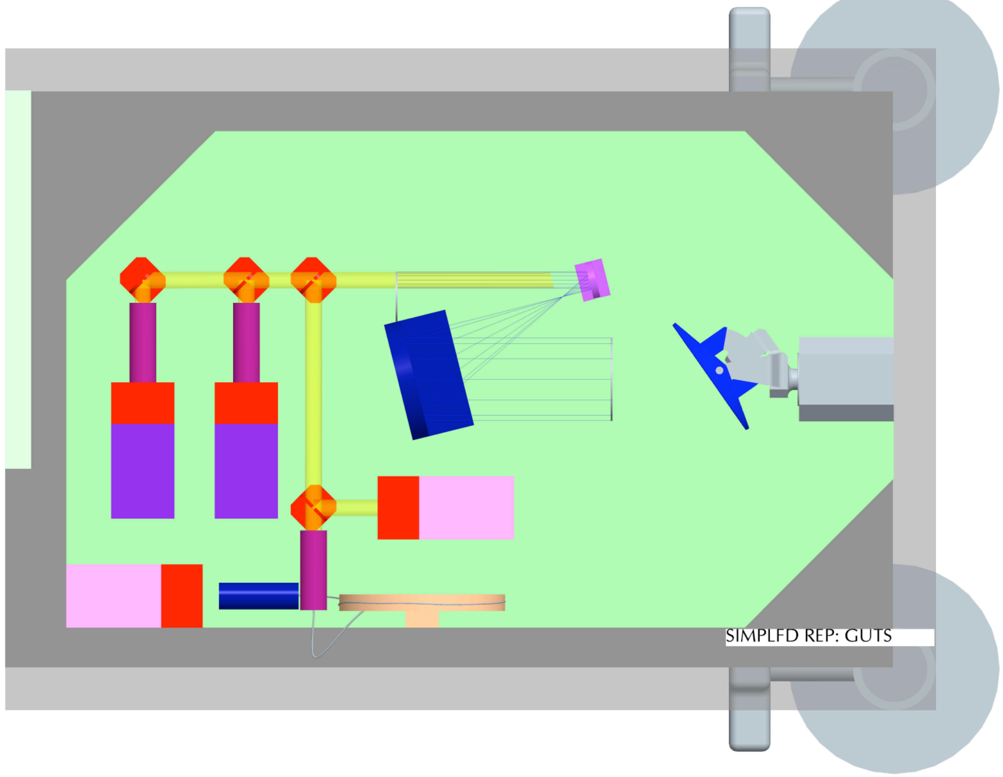
Summary

- More precise lunar ranging will enable unprecedented tests of Einstein's theory of General Relativity in addition to providing valuable data on the interior structure of the Moon and Earth-Moon interactions (tidal effects, etc.).
- New retroreflectors deployed at a pole or limb will greatly increase our ability to measure the lunar librations.
- New low-mass retroreflectors can be designed with lower errors and higher cross-sections that can be used with the existing SLR network.
- Stand-alone active systems appear feasible that have the potential for high precision and coverage.
- Active systems provide a pathfinder for interplanetary ranging instruments.
  - Precision ranging to Mars would provide additional tests of Einstein's theory of General Relativity, unique data on the structure of Mars, and even provide the most accurate determination of the mass of Jupiter.

Backup

Instrument Package





Equatorial Concept

Power

	Ranging	Lasercomm	RF Transmi	Standby
Power (W)	42.0	58.0	60.7	24

Mass

Item	Mass (Kg)
Laser Transponder Instrument	11.2
C&DH Electronics	6.8
Batteries	77.7
RF Subsystem	9.6
Instrument Structure	14.3
Thermal Subsystem	21.0
Solar Array	10.5
Second Battery Pack	94.9
TOTAL	**246.0**